Global Biogeochemical Cycles

Supporting Information for

High burial efficiency is required to explain mass balance in Earth's early carbon cycle

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Introduction

This file contains a compilation of literature estimates for various carbon fluxes that were used in the calculations presented in the main text.

$C_{carb\_weathering}$ (Tmol C/yr)	
11.8 – 14.4	(Holland, 1978)
12.5	(Berner et al., 1983)
12.5	(Garrels & Lerman, 1984)
24	(Lasaga et al., 1985)
13.3	(Berner & Berner, 1987)
12.3	(Gaillardet et al., 1999)
6.75	(Hartmann et al., 2009)
24.6	(Wallmann & Aloisi, 2012)
20	(Lee et al., 2016)
8	(Lenton et al., 2018)
14.7 ± 6.2	***Mean ±1 S.D.***

Table S1. Estimates of modern carbonate weathering flux.

$C_{org\_weathering}$ (Tmol C/yr)	
3.2	(Garrels & Lerman, 1984)
4	(Lasaga et al., 1985)
5	(Berner 1987)
5	(Berner & Canfield, 1989)
8.3	(Kump & Arthur, 1999)
7.5	(Lasaga & Ohmoto, 2002)
7.5 ± 2.5	(Holland, 2002)
7.5	(Bergman et al., 2004)
4.2	(Miller et al., 2011)
12 ± 4	(Wallman & Aloisi, 2012)
4.6 – 5.6	(Petsch, 2014)
5	(Lee et al., 2016)
7.5 ± 1.7	(Catling & Kasting, 2017)
3.75 – 7.75	(Lenton et al., 2018)
6.3 ± 2.3	***Mean ±1 S.D.***

Table S2. Estimates of modern organic carbon weathering flux.

$C_{metamorphic\_outgassing}$ (Tmol C/yr)	
1	(Kerrick, 1995)
2.5 ± 0.5	(Sano & Williams, 1998)
2.1 ± 0.7	(Hayes & Waldbauer, 2006)
3.5 ± 1.1	(Wallman & Aloisi, 2012)
1.5 – 3	(Lee et al., 2016)
2 ± 1	(Catling & Kasting, 2017)
2.2 ± 0.7	***Mean ±1 S.D.***

Table S3. Estimates of modern metamorphic outgassing.

$C_{mantle\_outgassing}$ (Tmol C/yr)	
2.2	(Hayes & Waldbauer, 2006)
4.3 ± 1.2	(Wallman & Aloisi, 2012)
6.5 ± 2.5	(Kasting, 2013)
1 – 7.5	(Lee et al., 2016)
6.5 ± 2.5	(Catling & Kasting, 2017)
6.6 ± 0.8	(Plank & Manning, 2019)
5.1 ± 1.8	***Mean ±1 S.D.***

Table S4. Estimates of modern mantle outgassing.

$C_{total\_outgassing}$ (Tmol C/yr)	
3.3 – 4.2	(Gerlach, 1991)
5.4 ± 3.8	(Williams et al., 1992)
7.5 ± 2.5	(Jarrard, 2003)
7 ± 3	(Berner, 2004)
7.9	(Bergman et al., 2004)
2.5 – 10.5	(Lee et al., 2016)
8.5 ± 2.5	(Catling & Kasting, 2017)
16.25	(Lenton et al., 2018)
8.2 ± 3.9	***Mean ±1 S.D.***

Table S5. Estimates of modern total carbon outgassing.

C_{org_burial} **(Tmol C/yr)**	
2.5	(Garrels & Perry, 1974)
10.5	(Berner, 1982)
10	(Holland, 2002)
5	(Berner, 2004)
10	(Catling & Kasting, 2017)
5	(Lenton et al., 2018)
7.2 $\pm$ 3.4	***Mean $\pm$1 S.D.***

Table S6. Published estimates of modern organic carbon burial.

C_{carb_burial} **(Tmol C/yr)**	
20	(Berner, 2004)
40	(Wallmann & Aloisi, 2012)
30	(Catling & Kasting, 2017)
20	(Lenton et al., 2018)
27.5 $\pm$ 9.6	***Mean $\pm$1 S.D.***

Table S7. Published estimates of modern carbonate burial.

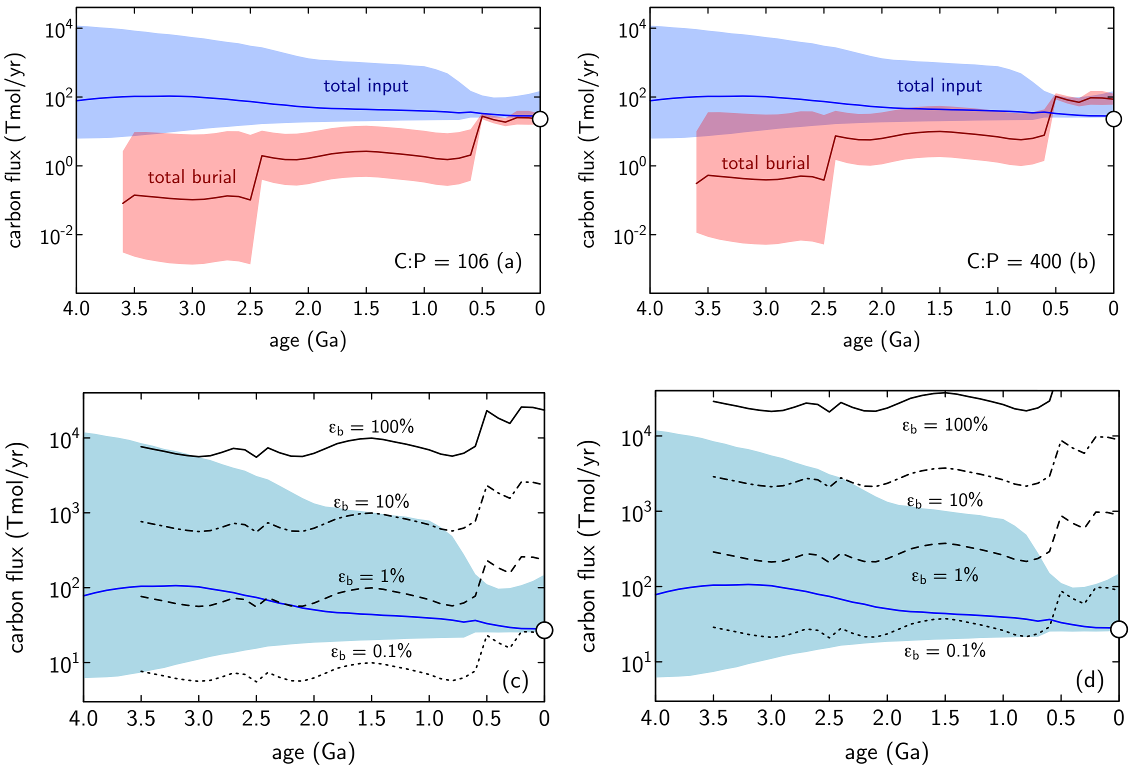

Figure S1. Effect of changing C:P ratio of primary producers. If it is assumed that primary producers had a C:P ratio of 400 (panels b & d) instead of the modern average of ~106 (panels a & c), then more C can be fixed for a given marine P inventory. This implies correspondingly higher C burial, though the uppermost limit on Archean C burial still falls short of balancing C inputs for most of the acceptable parameter space (panel b). Thus, while changing stoichiometry of primary producers may play a role in balancing the C budget in deep time, we find that it is insufficient to resolve the observed C cycle imbalance, and remains a highly uncertain variable in these calculations. Even if we do consider that C:P was ~400 in the Precambrian, burial efficiency likely needed to be much higher than it is today (panel d).

References

Berner, R. A. (1982). Burial of organic carbon and pyrite sulfur in the modern ocean: Its geochemical and environmental significance. *American Journal of Science, 282,* 451-473.

Berner, R. A., Lasaga, A. C., & Garrels, R. M. (1983). The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. *American Journal of Science, 283,* 641-683.

Berner, R. A. (1987). Models for carbon and sulfur cycles and atmospheric oxygen; application to Paleozoic geologic history. *American Journal of Science, 287,* 177-196.

Berner, E. & Berner, R. A. (1987). *The global water cycle*. Prentice-Hall.

Berner, R. A. & Canfield, D. E. (1989). A new model for atmospheric oxygen over Phanerozoic time. *American Journal of Science, 289,* 333-361.

Berner, R. A. (2004). *The Phanerozoic Carbon Cycle: CO_2 and O_2.* Oxford University Press. Bergman et al 2004

Catling, D. C., & Kasting, J. F. (2017). *Atmospheric Evolution on Inhabited and Lifeless Worlds*. Cambridge University Press.

Gaillardet, J., Dupre, B., Louvat, P., & Allegre, C. J. (1999). Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers. *Chemical Geology, 159,* 3-30.

Garrels, R. M. & Perry, E. A. (1974). In: *The Sea, Volume 5: Marine Chemistry*. Ed: Goldberg, E. D.

Garrels, R. M. & Lerman, A. (1984). Coupling of the sedimentary sulfur and carbon cycles; an improved model. *American Journal of Science, 284,* 989-1007.

Gerlach, T. M. (1991). Present-day CO_2 emissions from volcanoes. *Eos, 72,* 254-255.

Hartmann, J., Jansen, N., Durr, H. H., Kempe, S., & Kohler, P. (2009). Global CO_2-consumption by chemical weathering: What is the contribution of highly active weathering regions? *Global and Planetary Change, 69,* 185-194.

Hayes, J. M. & Waldbauer, J. R. (2006). The carbon cycle and associated redox processes through time. *Philosophical Transactions of the Royal Society B, 361,* 931-950.

Holland, H. D. (1978). *The chemistry of the atmosphere and oceans.* Wiley.

Holland, H. D. (2002). Volcanic gases, black smokers, and the Great Oxidation Event. *Geochimica Et Cosmochimica Acta*, *66*(21), 3811–3826.

Jarrard, R. D. (2003). Subduction fluxes of water, carbon dioxide, chlorine, and potassium. *Geochemistry, Geophysics, Geosystems, 4*.

Kasting, J. F. (2013). What caused the rise of atmospheric O_2? *Chemical Geology*, *362*, 13–25.

Kerrick, D. M., McKibben, M. A., Seward, T. M., & Caldeira, K. (1995). Convective hydrothermal CO2 emission from high heat flow regions. *Chemical Geology, 121,* 285-293.

Kump, L. R. & Arthur, M. A. (1999). Interpreting carbon-isotope excursions: carbonates and organic matter. *Chemical Geology, 161,* 181-198.

Lasaga, A. C., Berner, R. A., & Garrels, R. M. (1985). An improved geochemical model of atmospheric CO2 fluctuations over the pats 100 million years. In: *The carbon* *cycle and atmospheric CO2: Natural variations Archean to present*. Eds: Sundquist, E. T. & Broecker, W. S.

Lasaga, A. C. & Ohmoto, H. (2002). The oxygen geochemical cycle: Dynamics and stability. *Geochimica et Cosmochimica Acta, 66,* 361-381.

Lee, C.-T. A., Yeung, L. Y., McKenzie, N. R., Yokoyama, Y., Ozaki, K., & Lenardic, A. (2016). Two-step rise of atmospheric oxygen linked to the growth of continents. *Nature Geoscience*, *9*(6), 417–424.

Lenton, T. M., Daines, S. J., Mills, B. J. W. (2018). COPSE reloaded: An improved model of biogeochemical cycling over Phanerozoic time. *Earth-Science Reviews. 178,* 1-28.

Miller, C. A., Peucker-Ehrenbrink, B., Walker, B. D., & Marcantonio, F. (2011). Re-assessing the surface cycling of molybdenum and rhenium. *Geochimica et Cosmochimica Acta, 75,* 7146-7179.

Petsch, S. T. (2014). Weathering of organic carbon. In: *Treatise on Geochemistry*. Eds: Turekian, K. & Holland, H. D.

Plank, T. & Manning, C. E. (2019). Subducting carbon. *Nature, 574,* 343-352.

Sano, Y. & Williams, S. N. (1998). Fluxes of mantle and subducted carbon along convergent plate boundaries. *Geophysical Research Letters, 23,* 2749-2752.

Wallmann, K. & Aloisi, G. (2012). The global carbon cycle: Geological processes. In: *Fundamentals of Geobiology*. Eds: Knoll, A. H., Canfield, D. E., Konhauser, K. O.